EE-527: MicroFabrication

Plasma Processing Systems
Outline

• Fundamentals of plasmas
• Plasma sheaths and biasing
• Glow discharges
• Conservation equations
• DC plasmas
• RF plasmas
• Common plasma sources and configurations
• Excitation and matching
• Applications survey
What Are Plasmas?

• A gaseous-like state which contains both positively and negatively charged species, in roughly equal numbers.
  – Even though the particles are charged, the plasma itself is overall neutral.
• It does not have a definite size or shape; its extent is determined by its container.
• Sometimes called the 4th state of matter. (science over-simplified…)
• Most of the matter in the universe exists in a plasma state.
• Because it contains charged particles, it responds strongly to EM fields.
  – It can form filaments, beams, vortices, eddies, curtains, and layers.
• It usually involves the ionization of a neutral species into positive ions and negative electrons as part of its excitation process.
  – Recombination of the excited ions and electrons often produces luminous glows. The aurora or Northern lights are a prime example of a plasma.
  – The loss of energy through radiation requires a plasma to be continuously excited.
The Range of Plasmas

Plasma Density, \( n = n_i = n_e \), cm\(^{-3}\)

- Electron Energy, \( E_e \), eV
- Electron Temperature, \( T_e \), K

- RF processing
- Plasma
- DC glow discharges
- Earth's ionosphere
- High pressure arcs
- Laser plasmas
- Alkali metal plasmas
- Shock tubes
- Theta pinches
- Solar corona
- Fusion experiments
- Solar wind
- Interstellar
- Galactic

- Center of the Sun
- Crystalline Silicon at room temperature
- Laser plasmas
- Nuclear fusion

R. B. Darling / EE-527 / Winter 2013
Why Use Plasmas for Microfabrication?

• Reactions can be run faster, more localized, and with higher uniformity.
  – Plasmas can create high excitation energies without high substrate temperatures.
  – Ion bombardment can conform to the shape of the object.
  – Plasma processing allows efficient use of source materials.

• Highly anisotropic rates can be obtained.
  – This allows the final feature size to be closer to the mask size.
  – Deep etches with high aspect ratios can be created.

• High levels of process control can be achieved.
  – Plasmas are electrically excited, and their internal parameters can be directly controlled by the external excitation.

• Plasma processing provides good contamination control.
  – The process is carried out in a vacuum chamber, so no airborne contaminants enter the process.
  – A cold wall system produces less cross-contamination than a hot wall system.
  – Yields tend to be very high.
Characteristics of a Plasma

- **Particles:**
  - Neutral atoms or molecules (0)
  - Positively charged ions (+)
  - Negatively charged electrons (−)

- **Typical composition of a microfabrication etching plasma:**
  - Etch gas: $n_g \sim 10^{16}$ cm$^{-3}$, $T \sim 300$ K (~25 meV) (P~1 Torr)
  - Etch products: $n \sim 10^{15}$ cm$^{-3}$, $T \sim 300$ K (~25 meV)
  - Free radicals: $n \sim 10^{14}$ cm$^{-3}$, $T \sim 300$ K (~25 meV)
  - Plasma ions: $n_i \sim 10^{10}$ cm$^{-3}$, $T_i \sim 300$ K (~25 meV)
  - Plasma electrons: $n_e \sim 10^{10}$ cm$^{-3}$, $T_e \sim 10,000$ K (~1 eV)
  - Bombarding ions: $n \sim 10^{10}$ cm$^{-3}$, $T \sim 1,000,000$ K (~100 eV)

- **Conversion between temperature and energy units:**
  - $q/k_B = 11604$ K/eV.

- **Conversion between gas pressure and density (at $T = 300$ K):**
  - $n_g$ (cm$^{-3}$) = $3.250 \times 10^{16}$ P (Torr)

Note the rather low level of ionization: $\sim 10^{-6}$. 
Plasma Sheaths

- The interface between a plasma and an electrical conductor will deplete the electron density within a thin layer known as the sheath.
- The net positive space charge density within the sheath will cause the plasma to rise to a potential higher than that of the electrode. This potential difference is known as the sheath potential.
- Nearly all plasma processing occurs within the sheath.
- Ions, electrons, and neutrals leave the plasma at approximately their ideal gas impingement rates. Electrons are retarded by the sheath potential, while positive ions are accelerated by it.
- The bombarding ion flux is roughly set by the impingement rate.
- The bombarding ion energy is roughly set by the sheath potential.

\[
\frac{dN_i}{Adt} = \frac{N}{V} \left( \frac{k_B T}{2\pi m} \right)^{1/2} = \frac{P}{(2\pi mk_B T)^{1/2}} \quad P = nk_B T
\]
Sheaths for an Unbiased Plasma

- Plasmas are attached to any conductive surface by a sheath.
- The conductor depletes the sheath of electrons, giving it a positive space charge \( (n_i > n_e) \).
- This space charge biases the plasma positively, so that the plasma is the most positive potential in the system \( (V_P) \).
Sheaths for a DC Biased Plasma

- Application of an external bias $V_B$ alters the potential distribution of the system.
- The applied bias is absorbed entirely by one sheath, while the plasma remains at its potential of $V_P$.
- Ions bombarding the electrodes are accelerated by the potential difference across the corresponding sheath.
Plasma Oscillations

- Unforced oscillations in an unmagnetized plasma:
- Also known as Langmuir oscillations.
- The displacement of the electron cloud is \( s \) (in the \(-x\) direction as shown).
- This electron displacement creates a surface charge on opposite sides of the plasma.
- The surface charge produces an electric field which acts to restore the electron displacement.
- Plasma oscillations result.
Plasma Oscillations

• Unforced oscillation in a non-magnetized plasma:
  • $s =$ displacement of the electrons away from equilibrium where they compensate the positive ions, $n_i = n_e = n_o$.
  • A surface charge density of $\rho_s = \pm q n_o s$ is created on opposite sides of the plasma, leading to a restoring electric field $E_x = -qn_o s/\varepsilon_o$.
  • The force equation for the electrons is then
    $$ m_e \frac{d^2 s}{dt^2} = qE_x = -\frac{q^2 n_o s}{\varepsilon_o} = -m_e \omega_{pe}^2 s $$
  • The plasma oscillation frequency is:
    $$ \omega_p^2 = \omega_{pe}^2 + \omega_{pi}^2 \quad \omega_{pe}^2 = \frac{q^2 n_o}{\varepsilon_o m_e} \quad \omega_{pi}^2 = \frac{q^2 n_o}{\varepsilon_o M_i} $$
  • $f_p$ is typically 1-10 GHz.
  • Most RF excitation is below $f_p$, so the electrons move instantaneously with the applied field. An exception are ECR systems.

R. B. Darling / EE-527 / Winter 2013
AC Excitation of a Plasma

- AC excitation allows the use of insulating targets.
  - This is important for sputtering and etching of dielectric materials.
- AC excitation allows more flexible control of the potential distribution by means of capacitive voltage division and the creation of self-biasing electrode potentials.
  - Higher sheath potentials can be created, leading to higher ion energies incident upon the driven electrode.
  - Typically, obtain 100s of Volts instead of 10s of Volts.
  - Most importantly, these can be easily adjusted.
- AC excitation frequencies are chosen so that $\omega_{pi} < \omega < \omega_{pe}$.
  - The ions are too heavy to respond to this frequency and are effectively stationary.
  - The electrons are light and respond instantaneously to this frequency.
  - The electron cloud moves back and forth synchronously with the excitation.
  - Drive frequencies are usually in the mid-MHz.
Electrical Equivalent Circuit for a Plasma

\[ L = s_a + d + s_b \]

Plasma Admittance:

\[ Y_P = \frac{1}{R_P + j\omega L_P} + j\omega C_P \]

\[ C_P = \frac{\varepsilon_0 A}{d} \]

\[ L_P = \frac{1}{\omega_{pe}^2 C_P} \quad R_P = \frac{L_P}{\tau_m} \]
Electrode Asymmetry Effects

• The driven electrode is usually smaller than the grounded electrode, since the chamber itself is grounded.
• If driven through a blocking capacitor (capacitively coupled), the electrode asymmetry will affect the voltage distribution across the two sheaths, self-biasing the driven electrode to a negative voltage.
• With no blocking capacitor, $V_{bias} = V_b - V_a = 0$.
• With a large $C_B$, voltage divides by:

$$
\frac{V_a}{V_b} = \frac{C_b}{C_a}
$$

• $C_b > C_a$, so $V_{bias} < 0$.

$$
C = \frac{\varepsilon A}{s} \quad \text{for each sheath}
$$

If $s \propto V^{1/2}$ then

$$
\frac{V_a}{V_b} = \left(\frac{A_b}{A_a}\right)^2
$$
DC Glow Discharges

- Low pressure gas discharges involve ionization of the gas.
- Atomic, ionic, and molecular collisions are an essential part of these.
- Glow discharges are a sustainable ionization state, usually characterized by high voltage, low current, and a luminous output caused by recombination and radiative de-excitation of the gas ions.

Colors are approximately those of air at 10 millitorr ($N_2 + O_2$).
I-V Characteristic of a Low Pressure Gas Discharge

• Distinguish between glow discharge and arc discharge regions:
Electrical Excitation of a Gas Discharge

- Capacitively coupled (primarily electric field)
  - Use plates for coupling.
- Inductively coupled (primarily magnetic field)
  - Use coils for coupling.
- Electromagnetically coupled (TEM wave-heated)
  - Use antennas for coupling.
- DC glow discharge (primarily DC conduction)
  - Use conductive electrodes for coupling.
Electromagnetics: Maxwell’s Equations

Faraday’s Law: \( \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \)

Ampere’s Law: \( \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \)

Gauss’ Law: \( \nabla \cdot \mathbf{B} = 0 \)

Gauss’ Law: \( \nabla \cdot \mathbf{D} = \rho \)

Lorentz Force: \( \mathbf{f} = \rho (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \)

Permittivity: \( \mathbf{D} = \varepsilon \mathbf{E} \)

Permeability: \( \mathbf{B} = \mu \mathbf{H} \)

Conductivity: \( \mathbf{J} = \sigma \mathbf{E} \)
EM Sources, Potentials, and Boundary Conditions

• Sources:
  – Charge density: \( \rho = q(Zn_i - n_e) \)
  – Current density: \( \mathbf{J} = q(Zn_i \mathbf{u}_i - n_e \mathbf{u}_e) \)

• Potentials:
  – Scalar electric potential, \( \psi \)
  – Vector magnetic potential, \( \mathbf{A} \)

\[ \mathbf{E} = -\nabla \psi - \frac{\partial \mathbf{A}}{\partial t} \]
\[ \mathbf{B} = \nabla \times \mathbf{A} \]

\[ \nabla^2 \mathbf{A} - \mu \varepsilon \frac{\partial^2 \mathbf{A}}{\partial t^2} = -\mu \mathbf{J} \]
\[ \nabla^2 \psi - \mu \varepsilon \frac{\partial^2 \psi}{\partial t^2} = -\frac{\rho}{\varepsilon} \]

• Boundary conditions:
  \[ \mathbf{n} \times (\mathbf{E}_2 - \mathbf{E}_1) = 0 \]
  \[ \mathbf{n} \times (\mathbf{H}_2 - \mathbf{H}_1) = \mathbf{K} \]
  \[ \mathbf{n} \cdot (\mathbf{B}_2 - \mathbf{B}_1) = 0 \]
  \[ \mathbf{n} \cdot (\mathbf{D}_2 - \mathbf{D}_1) = \rho_s \]
Conservation Equations: Boltzmann Transport Theory

• The Boltzmann distribution function:
  – \( f(r,v,t) \) = the number of particles inside a volume of \( dr \) at \( r \) with velocities in the range of \( dv \) about \( v \) at time \( t \).

• Time evolution of the distribution function:
  – Collisionless Boltzmann’s equation (Vlasov Equation):
    \[
    \frac{df}{dt} = \frac{\partial f}{\partial t} + v \cdot \nabla_r f + a \cdot \nabla_v f = 0
    \]
  – Boltzmann’s equation with particle-particle collisions:
    \[
    \frac{df}{dt} = \frac{\partial f}{\partial t} + v \cdot \nabla_r f + \frac{F}{m} \cdot \nabla_v f = \frac{\partial f}{\partial t} \bigg|_C
    \]
  – The binary collision integral:
    \[
    \frac{\partial f}{\partial t} \bigg|_C = \int_{d\nu_2} \int_{d\phi_1} \int_0^{2\pi} \int_0^{\pi} \left( f'_1 f'_2 - f_1 f_2 \right) |v_1 - v_2| I \sin \theta_1 d\theta_1
    \]
Conservation of Particle Number

- Particle density:
  \[ n(r, t) = \int f(r, v, t) \, dv \quad [\text{cm}^{-3}] \]

- Particle flux density:
  \[ \Gamma(r, t) = \int v \, f(r, v, t) \, dv = n(r, t)u(r, t) \quad [\text{cm}^{-2} / \text{sec}] \]

- Zeroth moment of the BTE:
  \[ \frac{\partial n}{\partial t} + \nabla \cdot (nu) = G - R \quad [\text{cm}^{-3} / \text{sec}] \]
Conservation of Particle Momentum

• First moment of the BTE:

\[
\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = qn \left[ \mathbf{E} + \mathbf{u} \times \mathbf{B} \right] - \nabla \cdot \mathbf{\Pi} + \left. \frac{\partial \mathbf{p}}{\partial t} \right|_C
\]

- Momentum density: \( \mathbf{p}(\mathbf{r},t) = mn \mathbf{u}(\mathbf{r},t) \)
- Pressure tensor: \( \mathbf{\Pi}(\mathbf{r},\mathbf{r}) \); usually, \( \nabla \cdot \mathbf{\Pi} = \nabla \mathbf{P} \).

• Collisions of the particles with other species (\( \beta \)), the Krook collision operator:

\[
\left. \frac{\partial \mathbf{p}}{\partial t} \right|_C = -\sum_{\beta} mn v_{m\beta} \left( \mathbf{u} - \mathbf{u}_\beta \right) - m \mathbf{u} (G - R)
\]
Conservation of Particle Energy

• Particle kinetic energy density:

\[ w(\mathbf{r}, t) = \frac{3}{2} P(\mathbf{r}, t) + \frac{1}{2} mn \mathbf{u}^2 = \frac{1}{2} m \int \mathbf{v}^2 f(\mathbf{r}, \mathbf{v}, t) \, d\mathbf{v} \quad [\text{J / cm}^3] \]

• Isotropic pressure: (Ideal gas equation of state)

\[ P(\mathbf{r}, t) = \frac{1}{3} m \int |\mathbf{v} - \mathbf{u}|^2 f(\mathbf{r}, \mathbf{v}, t) \, d\mathbf{v} = n(\mathbf{r}, t) k_B T(\mathbf{r}, t) \]

• Second moment of the BTE:

\[ \frac{\partial}{\partial t} \left( \frac{3}{2} P \right) + \nabla \cdot \left( \frac{3}{2} P \mathbf{u} \right) + P \nabla \cdot \mathbf{u} + \nabla \cdot \mathbf{q} = \frac{\partial}{\partial t} \left( \frac{3}{2} P \right) \bigg|_c \]

• Heat flux density:

\[ \mathbf{q}(\mathbf{r}, t) = -\kappa \nabla T(\mathbf{r}, t) \quad [\text{J / cm}^2] \]
Planar RF Diode Plasma System

- Upper electrode
- Lower electrode
- Plasma
- Sheath
- Stainless steel vacuum chamber
- Gas feed
- Capacitance manometer
- Vacuum pump
Operational Modes

- **Plasma etching:** (reactive or sputter)
  - Set $V_{UE} = 0$ (Gnd), apply RF power to $V_{LE}$ (the substrate wafer).

- **Bias etching:** (reactive or sputter)
  - Capacitively couple RF power into $V_{LE}$. Lower electrode will create its own DC bias in an asymmetric system which can be adjusted to control the ion impact energy on the substrate.

- **Sputter deposition:**
  - Set $V_{LE} = 0$ (Gnd); apply RF power to $V_{UE}$ (the sputtering target).

- **Bias sputtering:**
  - Capacitively couple $V_{LE}$; apply RF power to $V_{UE}$. Lower electrode will create its own DC bias in an asymmetric system which can be adjusted to control the ion impact energy on the substrate.
Plasma Light Emission

- Plasmas are often luminous.
- Photons can be emitted when:
  - Electrons in excited atoms relax back to lower energy levels, or when
  - Electrons and ions recombine.
- The color depends upon the gas species and the energy levels involved:
  - Argon, relaxing back from an excited state: lavender
  - Neon, relaxing back from an excited state: reddish pink
  - Nitrogen, regaining an ionized electron: blue
  - Nitrogen, relaxing back from an excited state: red
  - Oxygen, relaxing back from an excited state: yellow-green
- Atomic emission spectra are more complex than just one color, but these hues are what are most commonly observed in plasma processing systems.
Dark Space Shields

- These are sheet metal shields placed around driven electrodes and held at ground potential.
- Their spacing to the driven electrode is smaller than the distance of a pair of plasma sheaths, so the discharge never forms within this gap.
- They suppress plasma formation through the creation of a dark space.
- They are also a means for creating electrode asymmetry.
Plasma Igniters

• RF-AC driven systems usually light automatically. Some planar RF diodes still provide an igniter circuit for stubborn situations.

• HV-DC driven systems usually require a high voltage pulse to ignite the plasma. The breakdown initiation voltage may be significantly higher than the sustaining voltage, but this required voltage may be much less when delivered with a high dV/dt.

• Most igniter circuits are high voltage pulse transformers, similar to the ignition coil of an automobile engine. Typical voltage pulses are 3-5 kV for a few milliseconds. Many are LC tuned to ring strongly.

• Lacking an igniter circuit, HV-DC systems must be brought up to an applied voltage significantly higher than the discharge sustaining voltage to start the plasma. Once lit, the applied voltage can be brought back down to its normal sustaining level. The firing voltage is a strong function of the gas species and pressure.
Automatic Pressure Control (APC) Systems

gas feed
poppet valve
and needle
valve
capacitance
manometer
stepper motor
actuator
vacuum pressure
gauge
valve position
controller
process vacuum chamber
gate valve
variable conductance
throttle valve
(APC valve)
venetian blind style
turbo pump
to roughing pump

R. B. Darling / EE-527 / Winter 2013
Automatic Pressure Control (APC) Systems

• Gas pressure is a critical control variable for a plasma system, as well as in other low pressure deposition systems, such as LPCVD.

• MFCs can be used to provide accurate gas feeds, but the pumping speed and the gas consumption rate may vary, making this a difficult means to control the chamber pressure. Time lag is also a problem.

• A better solution is to control the pumping speed through a throttle valve on the pumping port. These are known as automatic pressure control valves (APC valves).
  – Most use a stepper motor to control the position of a set of venetian blind louvers.
  – The chamber pressure is monitored through a capacitance manometer, and compared against the process set point.
  – A valve position controller is used to drive the stepper motor to adjust the louvers and vary the pumping speed.

• This method of automatic pressure control has very fast response when used with a high speed vacuum pump, e.g. a turbo or a cryo pump.
Technology Demands on Plasma Processing Systems

• Planar RF diodes are very versatile and can handle many applications in microfabrication. However, they operate only at relatively low plasma densities, $n_i = n_e \sim 10^{10}$ cm$^{-3}$, and have comparatively low process throughput.
  – Deposition and etch times for physical (non-chemical) processes are in the range of 10 to 100 nm/min, which is a bit slow for manufacturing needs.
  – DC glow discharge systems are even slower.

• Many plasma system technologies have been developed to increase the plasma density so as to improve this throughput.
  – Magnetrons and S-gun sputtering systems: increase $\sim 10X$
  – Inductively coupled plasma (ICP) etch systems: increase $\sim 10X$
  – Electron cyclotron resonance (ECR) etch systems: increase $\sim 100X$
Planar Magnetron Plasma Sources

- Static magnetic fields can be used to increase the flight path of electrons, which significantly increases their chances of ionization.
- The enhanced ionization rate increases the plasma density.
- When \( E \) and \( B \) are coaxial, a helical electron path is produced.
- When \( B \) is parallel to an electrode face, emitted electrons will follow a semi-circular path back into the electrode, creating new secondary electrons.
- Permanent magnet assemblies are often constructed to create toroidal “race tracks” for electrons, enhancing the ionization along this zone.
- The enhanced erosion of the electrode along these tracks makes them attractive for sputtering sources.

\[
\frac{m_e v^2}{r} = q v B \\
\]  
\[
\frac{m_e v}{q B} = r
\]

R. B. Darling / EE-527 / Winter 2013
Varian Magnetron Sputtering Source

Figure from Glaser & Subak-Sharpe, Integrated Circuit Engineering, 1977.
This design works well for small target sizes, 1-inch up to 6-inch, and is commonly used in many R&D systems. Target utilization is generally high, > ~ 75%.
Planar Inductively Coupled Plasma (ICP) System

- gas feed
- planar helical RF "pancake" coil
- RF bias on substrate
- vacuum pump
- stainless steel side walls
- glass top plate
- stainless steel bottom plate
- plasma
- substrate
Cylindrical Inductively Coupled Plasma (ICP) System

- Gas feed
- Vacuum pump
- Annular RF drive coil
- Stainless steel top plate
- Glass side walls
- Stainless steel bottom plate
- Plasma
- Substrate
- RF bias on substrate
ICP Etching System

gas feed

top electrode
gas showerhead
(grounded)

substitute

bottom electrode
substrate platten
(RF driven)

dark space shield

capacitance
manometer

to APC valve,
gate valve, and
turbo pump

to RF matching unit
and generator
Electron Cyclotron Resonance (ECR) Plasma System

• The RF excitation frequency is chosen to match to the electron cyclotron resonance of the plasma: \( \omega = \omega_{pe} \).
  – This is usually based around the 2.45 GHz ISM frequency band.

• Since the excitation frequency is fixed, tuning to the resonance involves tuning the chamber geometry to support a cavity resonance at this frequency as well as adjusting the gas pressure to support a plasma density at precisely the value needed for the 2.45 GHz ECR resonance.

• At the plasma frequency, the impedance of the plasma becomes its maximum magnitude and real-valued.
  – Refer to the plasma equivalent circuit model.
  – The plasma absorbs the maximum amount of input RF power at this point, in preference to the sheaths. This higher level of excitation allows significantly higher plasma densities to be obtained; however, these are only within a restricted region of the chamber where the fields of the cavity resonance and the plasma ECR oscillation conditions are simultaneously met.
RF Generators for Plasma Excitation

- Typically 500 – 2000 Watts, sinusoidal waveform
- Frequencies: Industrial, Scientific & Medical (ISM) bands:
  - 6.765 – 6.795 MHz; 6.780 MHz center frequency
  - 13.553 – 13.567 MHz; 13.560 MHz center frequency
    - Most common for RF plasma sources
  - 26.957 – 27.283 MHz; 27.120 MHz center frequency
  - 40.66 – 40.70 MHz; 40.68 MHz center frequency
  - 433.05 – 434.79 MHz; 433.92 MHz center frequency
  - 902 – 928 MHz; 915 MHz center frequency
  - 2.400 – 2.500 GHz; 2.45 GHz center frequency
    - Microwave ovens
    - IEEE 802.11/WiFi
      - Most common for microwave plasma sources such as ECR sources
  - 5.725 – 5.875 GHz; 5.80 GHz center frequency
    - IEEE 802.11/WiFi
- Low bands are factors of 2 to contain even harmonics.
RF Impedance Matching – 1

- Within the transmission line, need to consider forward and backward propagating voltage and current waves:
RF Impedance Matching – 2

- For maximum RF power transfer from the generator to the load, need to make $Z_S = Z_L^*$, a complex conjugate match.
- The generator and load are connected by a transmission line cable with $Z_0 = 50 \ \Omega$.
- The generator is usually designed to have $Z_S = 50 \ \Omega$.
- Voltage reflection coefficient at the load:

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0}$$

- Voltage Standing Wave Ratio (VSWR):

$$\text{VSWR} = S = \frac{|V(x)|_{\text{max}}}{|V(x)|_{\text{min}}} = \frac{1 + |\Gamma_0|}{1 - |\Gamma_0|}$$
The Smith Chart

Re(\(\Gamma\))

Im(\(\Gamma\))

inductive reactance
capacitive susceptance

capacitive reactance
inductive susceptance

to source
short

open
to load
RF Impedance Matching – 3

• At $f = 13.56$ MHz, $\lambda_0 = 22.11$ m.
• For a cable with a velocity factor of 0.67, $\lambda = 14.81$ m.
• A $\lambda/4$ transformer will be 3.70 m = 12.15 ft long.
• For these long wavelengths, tuning stubs and quarter-wave transformers are physically large, so tuning elements are more commonly lumped reactive elements.
• Directional couplers are used to monitor forward and reverse power flow.
• Tuning involves maximizing the forward power while minimizing the reverse power.
• Both manual and automatic systems exist for this.
Impedance Matching to the Plasma

- The impedance of the plasma system load depends upon the state of the plasma! It is usually *not* 50 Ω.
- A Catch-22:
  - The impedance changes drastically whether the plasma is lit or not.
  - To light the plasma, sufficient RF power must be applied.
  - For sufficient RF power to be applied, the impedances must be matched.
  - To match the impedances, the tuning network must be first adjusted to the unlit plasma load impedance.
  - Once the plasma lights, the impedance changes and the RF power is no longer matched. The plasma may immediately extinguish.
- Continuous tuning of the RF impedance match is required for steady power input into the plasma.
  - Most systems employ an automatic RF tuner to do this.
- An plasma igniter circuit is often employed to light the plasma.
  - This then requires less initial tuning after the plasma has been lit.
RF Matching Networks

- Require a minimum of two tuning elements to cancel the load reactance and transform the resistance to 50 Ω.
- Most are based upon LC networks.
- Some use less common variable inductors: rotary inductors, variable transformers, etc.

![Diagram of Pi-tuning network and T-tuning network]
Multi-Target, Multi-Function Systems

- Example: Perkin-Elmer Randex 2400 J-arm Sputter/Etch System:
The Realms of Thin Film Vapor Phase Deposition

- PHYSICAL
  - Evaporation (PVD)
  - Sputtering

- CHEMICAL
  - CVD
  - PECVD

- NO PLASMA
- PLASMA
Sputtering

• Sputtering is the simplest processing application of plasmas.
• It involves only physical bombardment and recoil without any chemistry considerations.
• It is an effective method for deposition of many materials with less heat and greater source utilization than evaporation.
• It is generally the preferred method for depositing metals in the microelectronics industry.
• The downside is that it requires much larger high-purity targets that are usually at least as large as the substrate array to be coated.
Sputtering

• Like evaporation, sputtering is a physical process, but the transport of the source material to the substrate is produced by an energized plasma.

• A plasma is used to create a source of impinging ions which are accelerated into a target which is the source material.
  – Argon is the most common gas used for sputtering, but it may be mixed with other gases in certain situations.

• The impinging ions knock loose atoms of the target by physical sputtering.

• The sputtered atoms travel back through the plasma and are deposited on the substrate.
Advantages of Sputtering over Evaporation

• Sputtering does not require the source or target material to be heated to its evaporation temperature.
  – It is a “cold wall” process, which greatly increases the cleanliness and reduces the contamination and degradation of a hot wall reactor.

• Sputtering provides better utilization of the source or target material.
  – Sputtering does not coat the chamber walls like evaporation, and so most of the target material gets used for deposition on the substrates.

• Sputtering does not cause much compositional change in the source material.
  – Alloys and mixed composition targets can be directly deposited.
Disadvantages of Sputtering

• An entire target must be obtained before any sputtering can be done.
  – Sputtering targets are expensive in comparison to evaporation charges, although they last for long periods of time.

• Uniformity requires effort.
  – For planar sputtering systems, the target must usually be sized 1-2 inches greater in diameter than the wafer to be coated. For example, achieving good uniformity over a 6-inch wafer usually requires an 8-inch target to reduce edge effects.
  – For S-gun magnetron sputtering systems, the target in the gun can be smaller than the wafer size, but the distribution pattern of the gun must be accounted for. S-guns are usually not practical for wafers larger than 6-inches in diameter.
DC Diode Sputtering System

Figure from Glaser & Subak-Sharpe, Integrated Circuit Engineering, 1977.
DC Triode Sputtering System

Figure from Glaser & Subak-Sharpe, Integrated Circuit Engineering, 1977.
Reactive Sputtering

- Sputtering typically produces a high density of “dangling bonds” in the deposited film which reduce the quality of its physical and chemical properties.
- Reactive sputtering is a means by which these “dangling bonds” can be properly terminated to produce a high quality thin film.
- Example: Sputtering of SiO$_2$: Use Ar + O$_2$.
- Example: Sputtering of Si$_3$N$_4$: Use Ar + N$_2$. 
Sputtering Yield

Argon ions are the incident species.
Sputtering Yield

- Sputtering yield \( (S) \) is the number of ejected atoms of the target for each incident bombarding ion.
- The sputtering yield typically has a threshold energy to achieve any yield at all:
  \[
  E_{th} = \frac{U_0}{\gamma(1-\gamma)} \quad \gamma = \frac{4M_1M_2}{(M_1 + M_2)^2}
  \]
- The threshold energy is minimized for \( M_1 = M_2 \).
- The threshold energy is typically 30 eV to 120 eV.
- In the limit of high incident ion energy, the sputtering yield follows an inverse cosine law:
  \[
  S \propto \frac{M_{gas}}{M_{target}} \cdot \ln E \cdot \frac{1}{E \cos \theta}
  \]
Saturation of Sputtering Yield with Ion Energy

Figure from Glaser & Subak-Sharpe, Integrated Circuit Engineering, 1977.
Sputter Deposition

- Sputtered atoms must pass back through the plasma to reach the substrate.
- Although these atoms are nominally neutral, they still collide with the energized ions of the plasma, and their trajectories become randomized.
- This randomization gives the sputtered atom flux the ability to coat sidewalls much more effectively than evaporation which is usually directional.
- This sidewall or step coverage is reduced somewhat for magnetron S-gun sources which separate the plasma from the substrates.
Step Coverage

• The thickness of sidewall coating depends upon the angle of incidence and the directionality of the source:
Shadowing

- Surface features, such as an existing trench, can produce shadowing of the deposited film.
- This can be used to advantage in some cases.